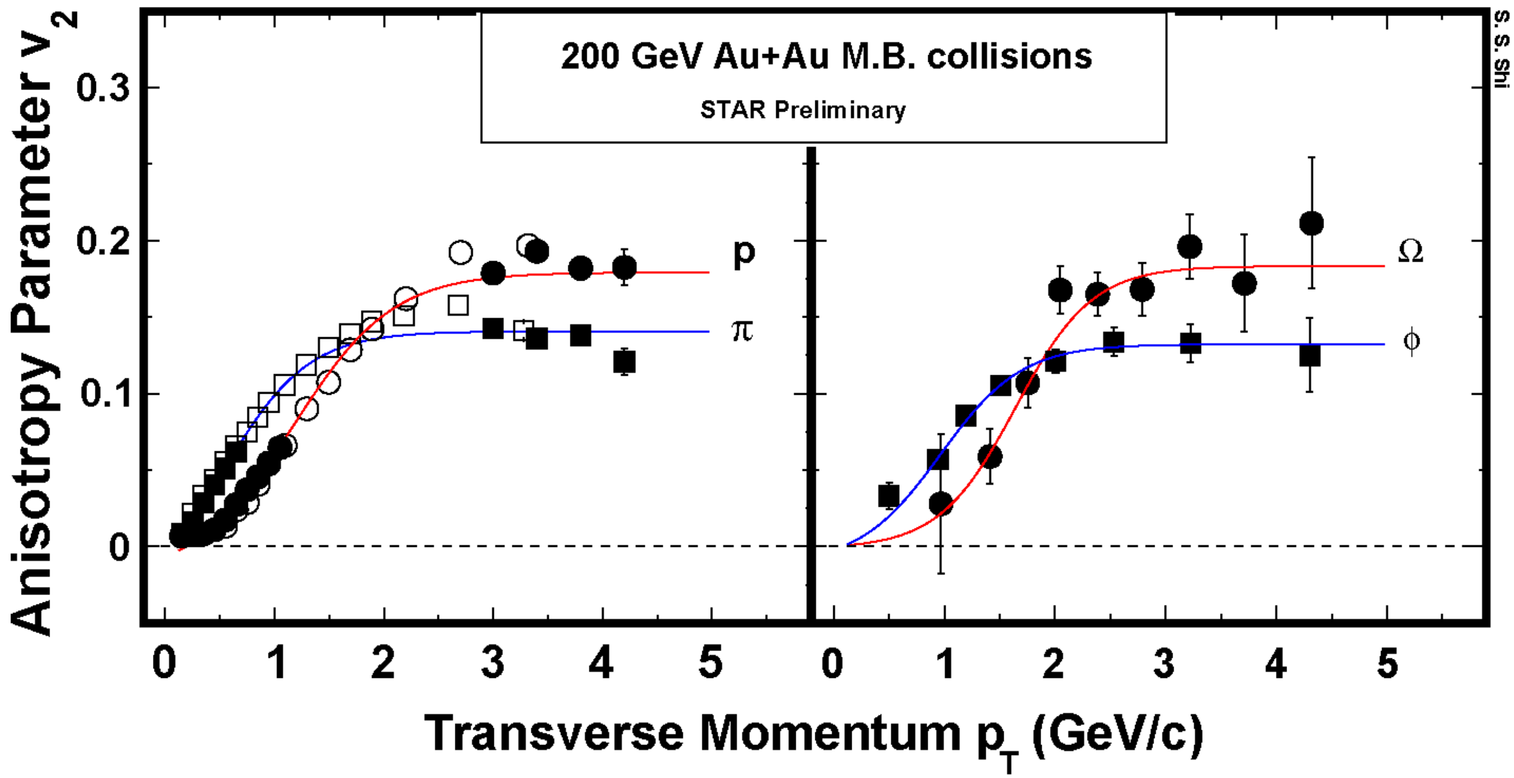
Summary of STAR Flow Results

Aihong Tang for the STAR Collaboration

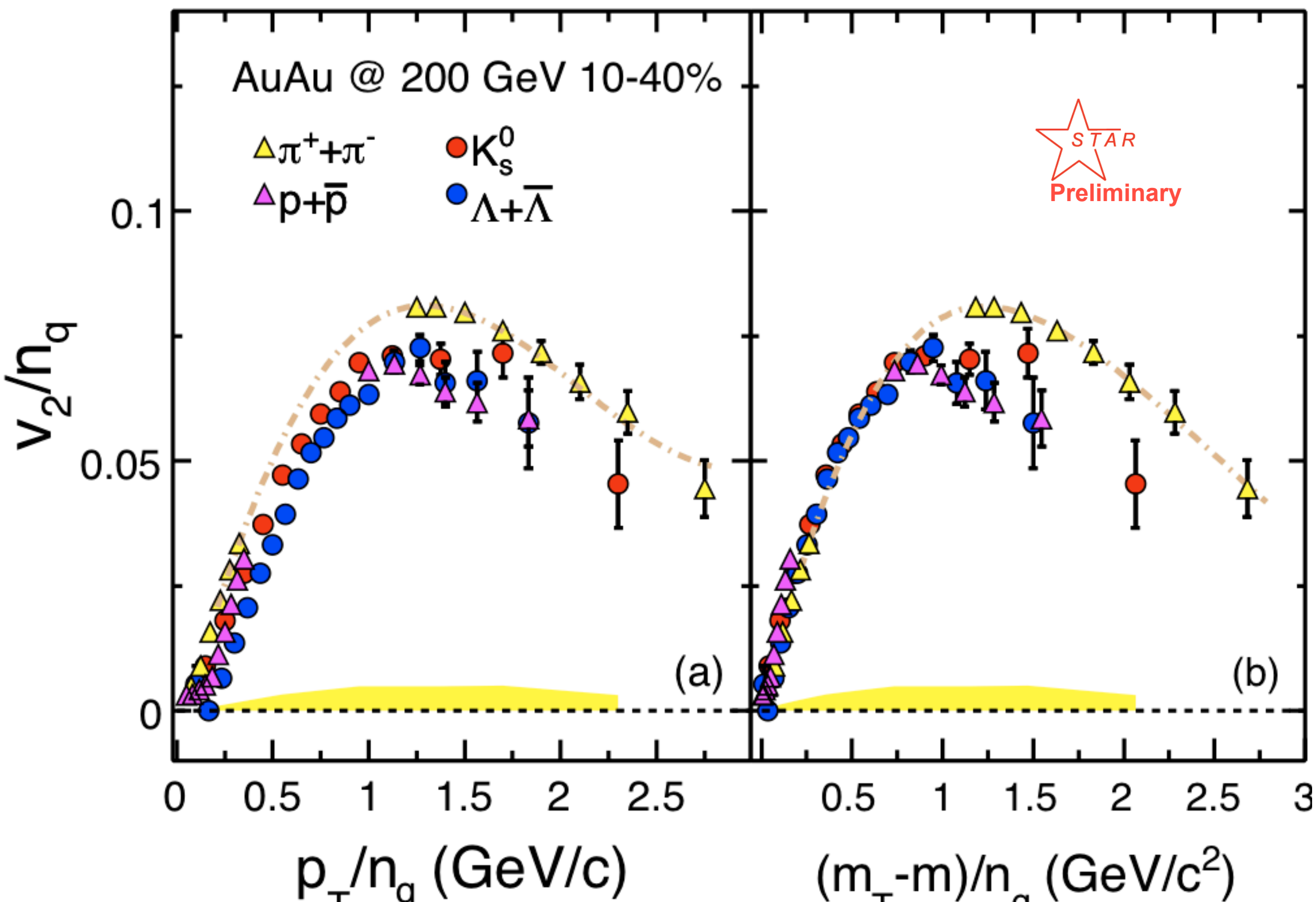
Partonic Collectivity



PHENIX π and p: nucl-ex/0604011v1
NQ inspired fit: X. Dong et al. Phy. Let. B 597 (2004) 328-332

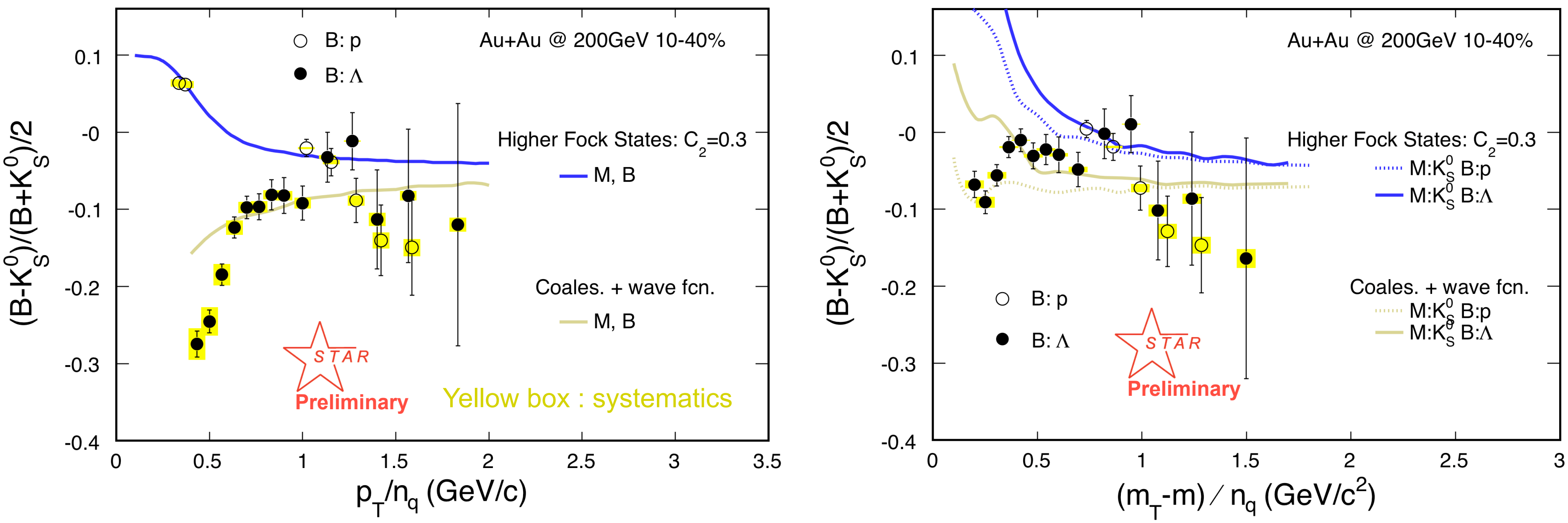
Partonic collectivity at RHIC : case closed.

A Close Look at the NCQ Scaling



New results with a forward reaction plane detector (FTPC) which reduces systematic uncertainties. Best available data-set for studying NCQ scaling.

A Close Look at the NCQ Scaling

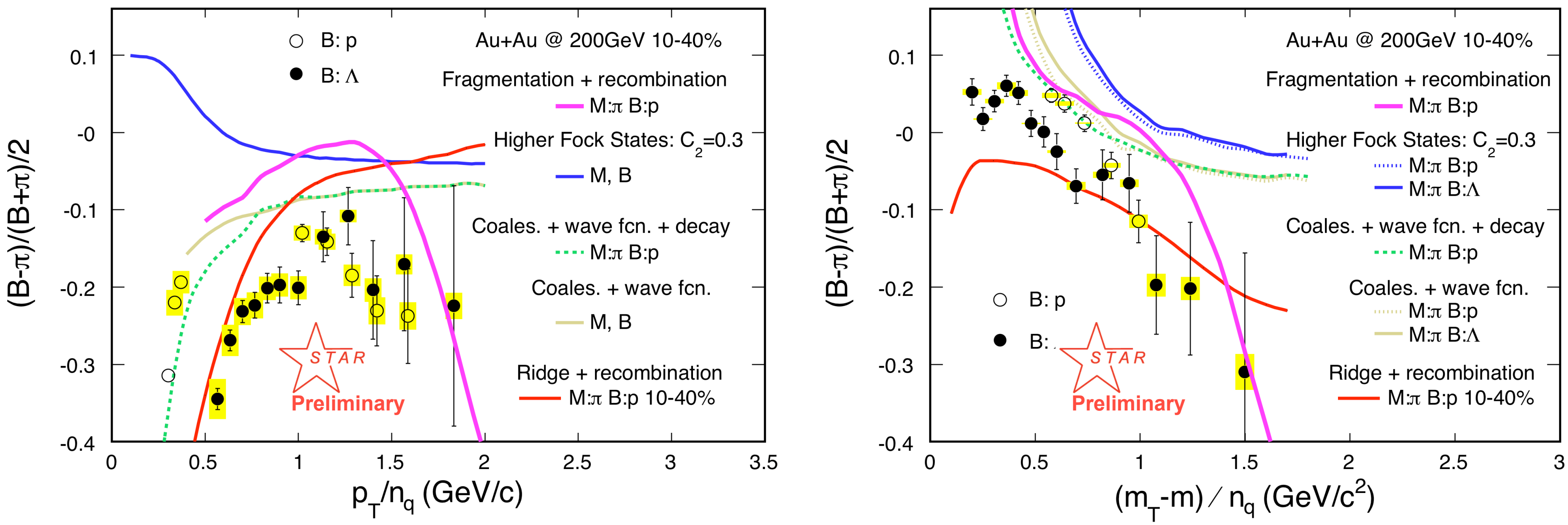


Curves : V.Greco and C.M.Ko, PRL 70 024901 (2004); B. Muller, R.J.Fries and S.A.Bass, PLB 618 77 (2005)

The large deviation at low pt in plot made with p_t/n_q is due to mass splitting, which can be reduced by plotting with $(m_T-m)/n_q$

Models with realistic effects describe the difference between kaons and baryons well.

A Close Look at the NCQ Scaling



Curves : V.Greco and C.M.Ko, PRL 70 024901 (2004); B. Muller, R.J.Fries and S.A.Bass, PLB 618 77 (2005)
C.B.Chiu, R.C. Hwa and C..B. Yang, PRC 78 044903 (2008), R.J. Fries, B.Muller, C. Nonaka and S.A. Bass, PRC 68 044902 (2003)

In the range of $0.5<p_T/n_q<1.5$ (GeV/c), the deviation between pions and baryons is ~20%, while models with realistic effects can tolerate up to only 5%.

m_T scaling at low m_T – m and NCQ scaling at intermediate p_t are two separate scalings, they should not be confused. An apparent deviation in $(m_T\text{-}m)/n_q$ can become less significant if viewed with (p_T/n_q)

Seemingly decreasing trend observed at large p_T, best described with Frag. +Reco. model

Thermalization and Flow

What is thermalization ?

Equal partition of energy.

How is the thermalization achieved ?

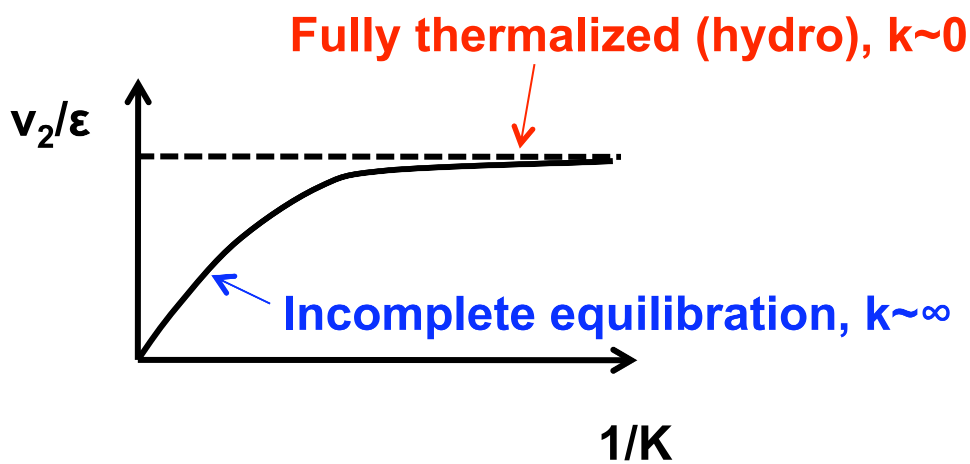
Interactions !

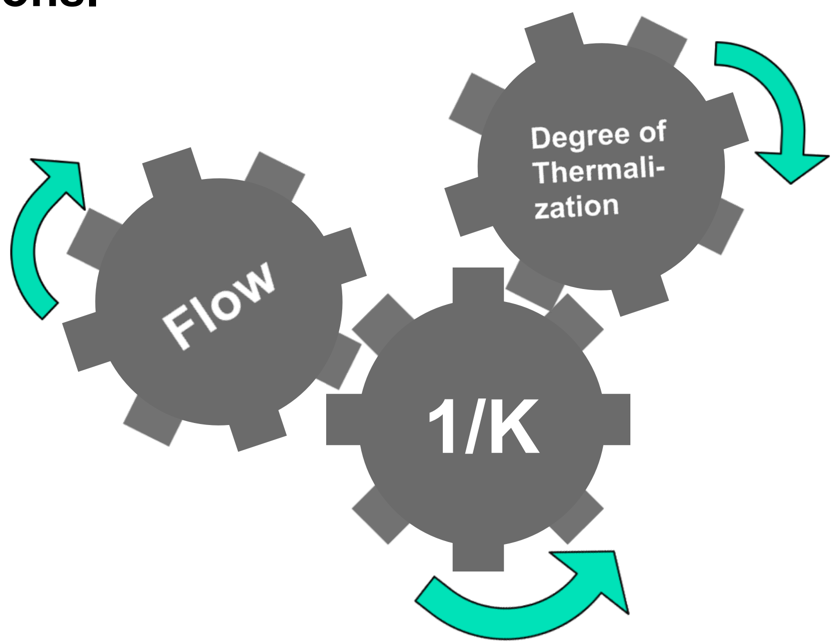
How do we address the degree of thermalization ?

Knudsen number ($K=\lambda/R$), $1/K$ ~ # of collisions.

What observable is sensitive to 1/K ?

Flow !

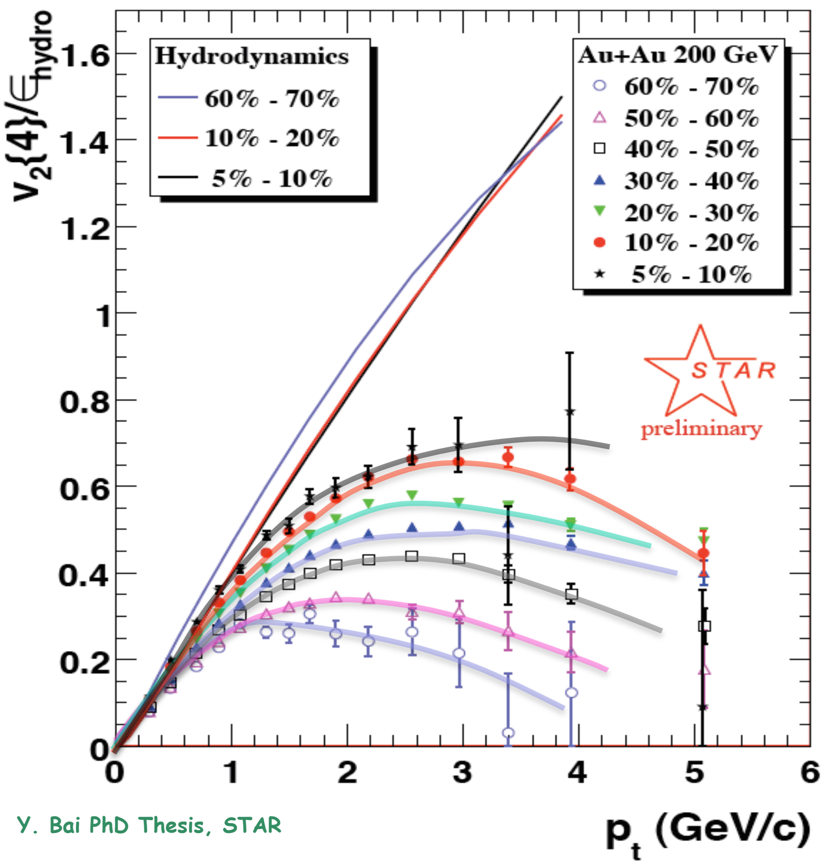




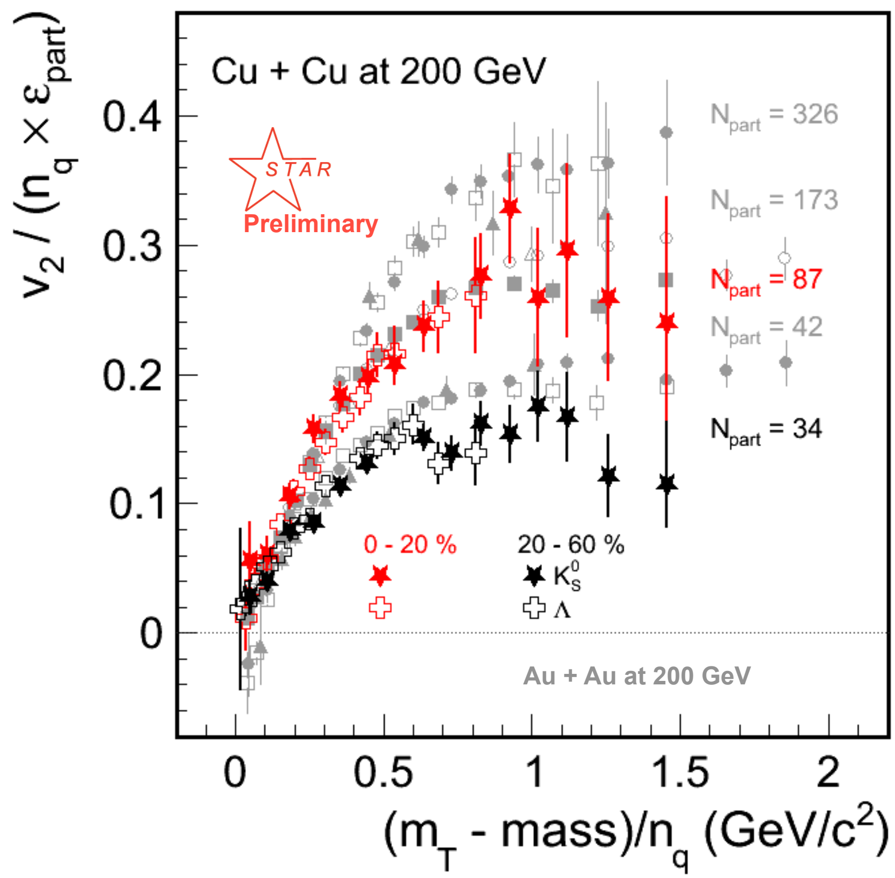
How to dial 1/K

$$\frac{1}{K} = \sigma c_s \frac{1}{S}\frac{dN}{dy}$$

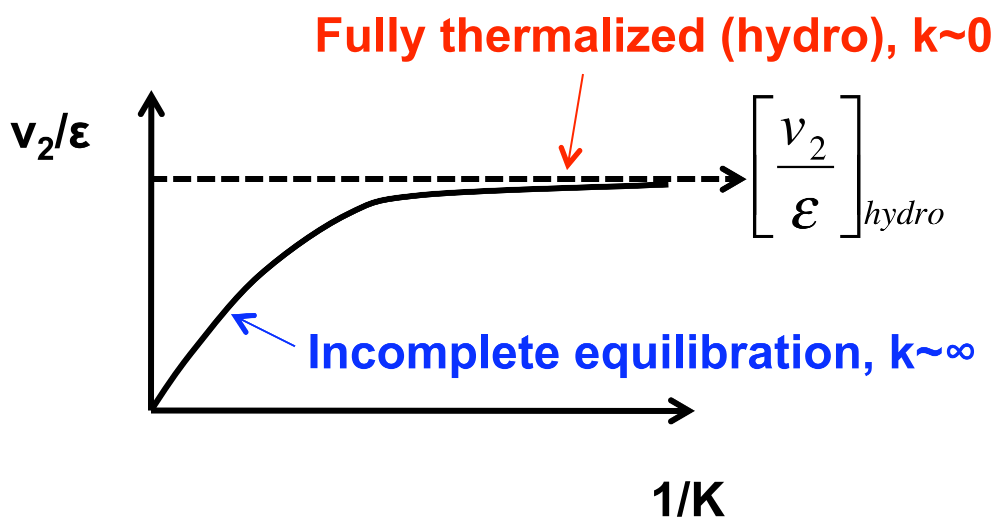
1. **Change the centrality.**
2. **Change the system size.**



Y. Bai PhD Thesis, STAR



What do we learn from dialing 1/K ?



$$\left[\frac{v_2}{\varepsilon}\right]_{hydro}$$

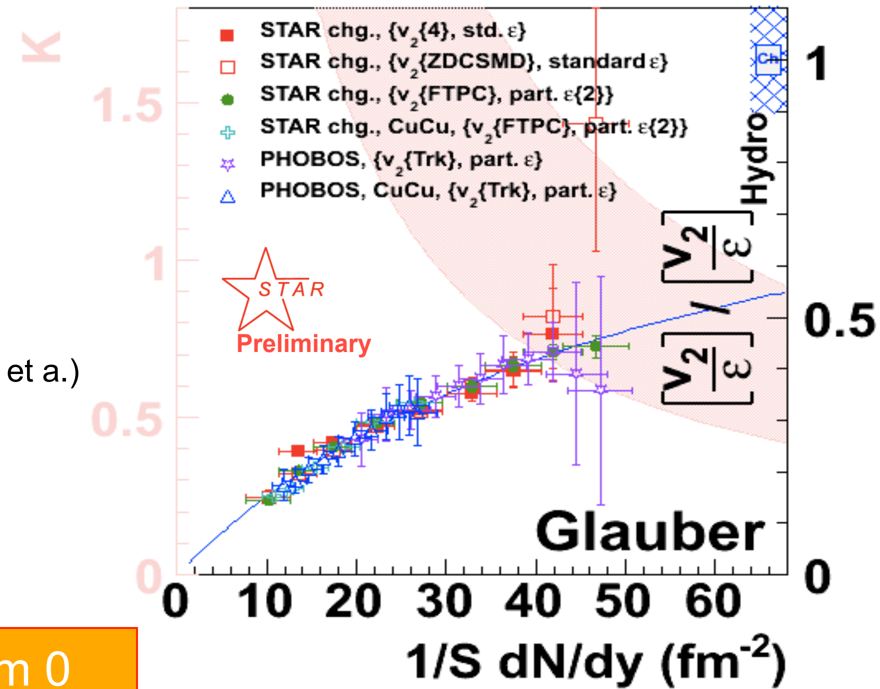
$$1-\left[\frac{v_2}{\varepsilon}\right] / \left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto K$$ When K is small (Hydro Limit)

$$\left[\frac{v_2}{\varepsilon}\right] / \left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto 1/K$$ When K is large (Low Density Limit)

$$\left[\frac{v_2}{\varepsilon}\right] / \left[\frac{v_2}{\varepsilon}\right]_{hydro} = \frac{1}{1+K/K_0}$$

$K_0 = 0.7$ from both AMPT and 2-D transport model (Ollitrault et a.)

$$\frac{1}{K} = \frac{R}{\lambda} = \sigma c_s \frac{1}{S}\frac{dN}{dy}$$



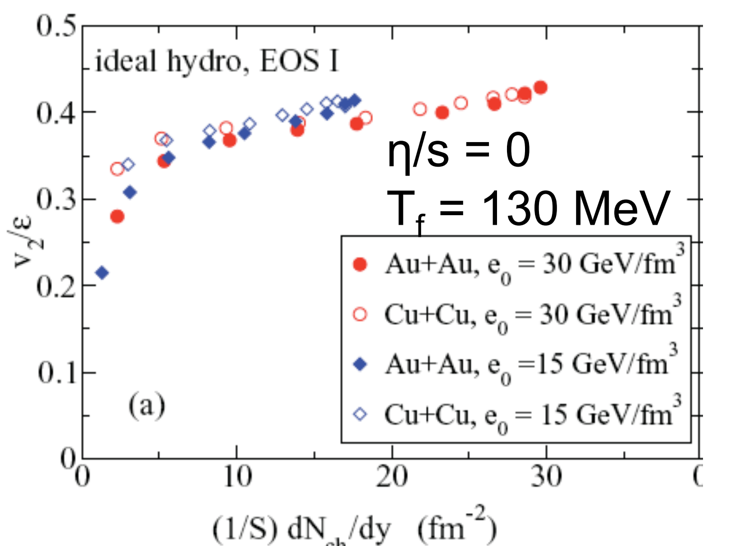
Knudsen number is considerably away from 0 (K=0 is required by ideal Hydro.)

Through this talk, $[v_2/\varepsilon]_{hydro}$ denotes the saturated value extracted from Knudsen fitting.

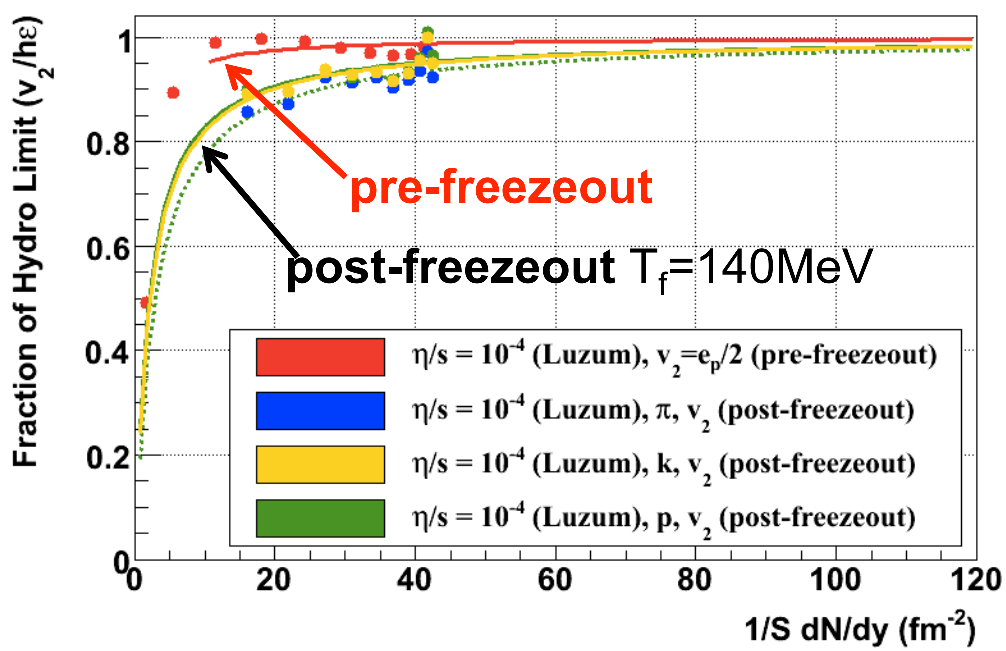
Side Remarks with Knudsen Fit

- We all agree that we have to be very careful with Knudsen Fit (Nagle, Steinberg and Zajc, arXiv:0908.3684):
    - The mixture ratio (x) between N_bin and N_part we used is 0.14 (PHOBOS used 0.13)
    - We use fMCKLN, which has the fluctuation folded in and can produce dN/dy well.
    - The correlated error are propagated according to the standard procedure in pdg book.
    - We have tried different formula (but not the Pade formula for a reason – see backup slide) to fit our data and examined χ^2 distributions.
    - – All of the above have been included in the systematics of results shown at QM09.
- The Knudsen Fit gives us the **effective** η/s. Any effect that contributes to the curvature of v_2/ε vs. 1/S dN/dy will be captured as viscosity – **an upper limit on η/s**.

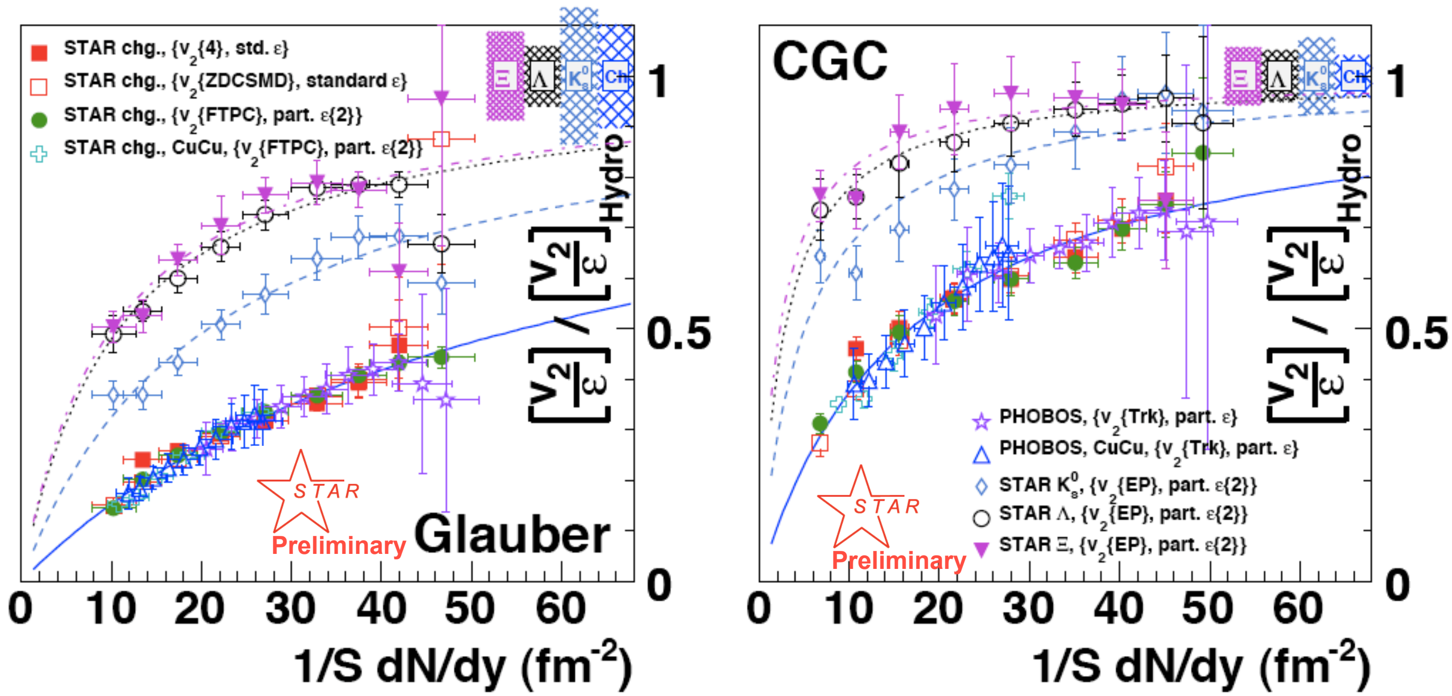
Example : Freeze-out at finite temperature is interpreted as viscosity by Knudsen fit.



H. Song and U. Heinz, PRC 78 024902 (2008)



What causes the mass hierarchy of curvature ?



The heavier the mass, the larger the curvature.

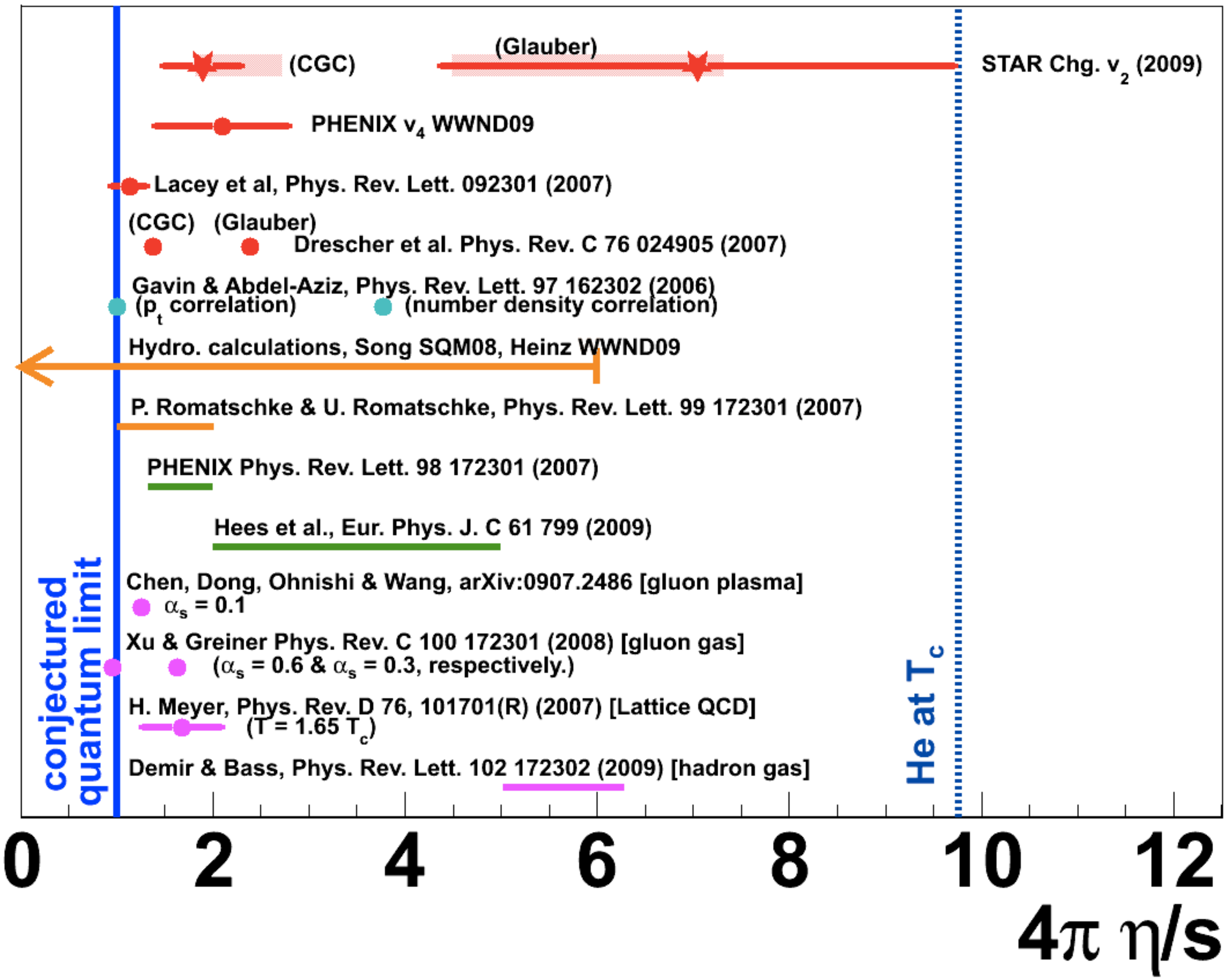
Ideal hydro[1] does not have the mass hierarchy of the curvature, adding the viscous effect[1] and hadronic rescattering[2] gives the opposite order of the mass hierarchy (see backup slides).

So far only AMPT gives the right order of mass hierarchy of curvature.

Note : Through this talk, $[v_2/\varepsilon]_{hydro}$ denotes the saturated value extracted from Knudsen fitting, it is not necessarily the same as limits from various hydro models.

1. Luzum & Romatschke, private communication
2. Hirano, private communication

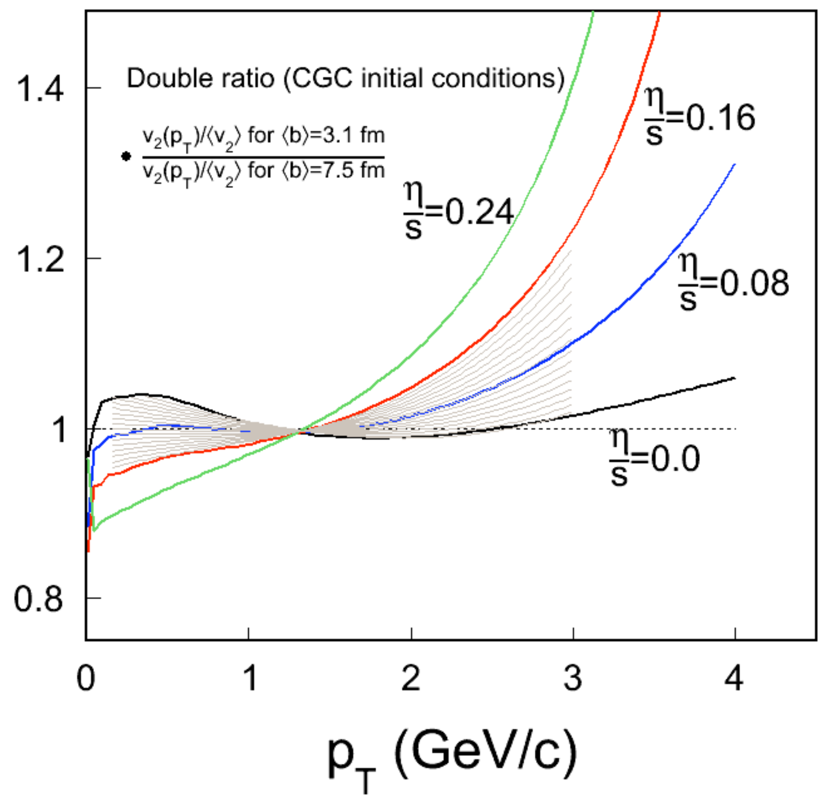
World Collection of η/s



Color code:
Flow
p_t correlations
Viscous Hydro.
Heavy Flavor
Other

The upper limit of η/s is still below He at T_c

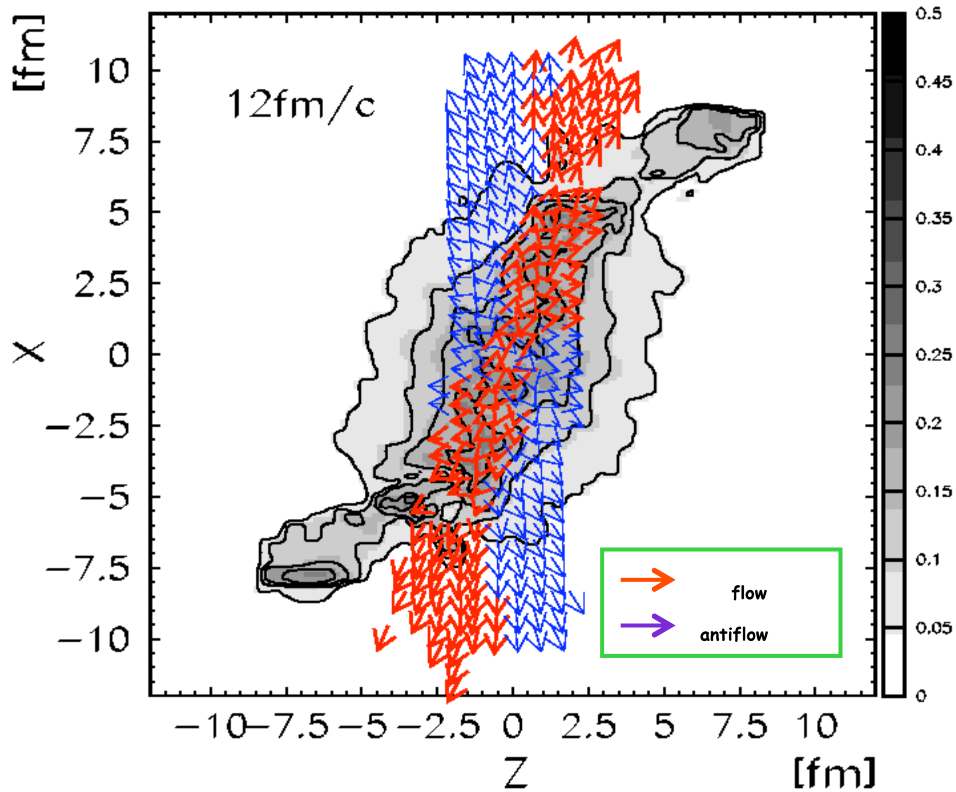
η/s obtained by comparing $v_2(p_t)$ shape to Hydro

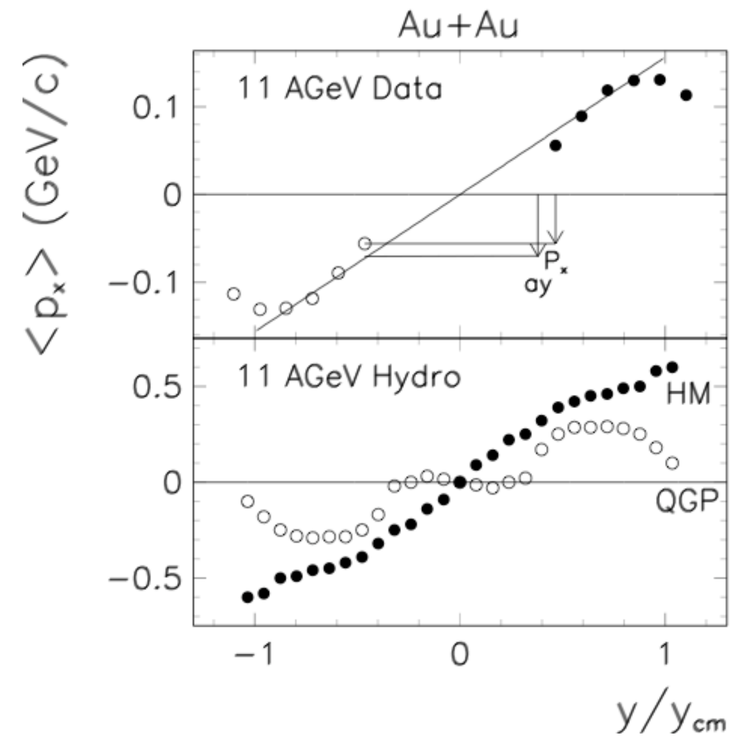


See Talk by S.Shi

Utilizing the shape change of $v_2(p_t)$ as a function of centrality to constrain η/s from QGP fluid phase. Consistent with previous claims made by Hydro. models.

Anti-flow / 3rd flow component

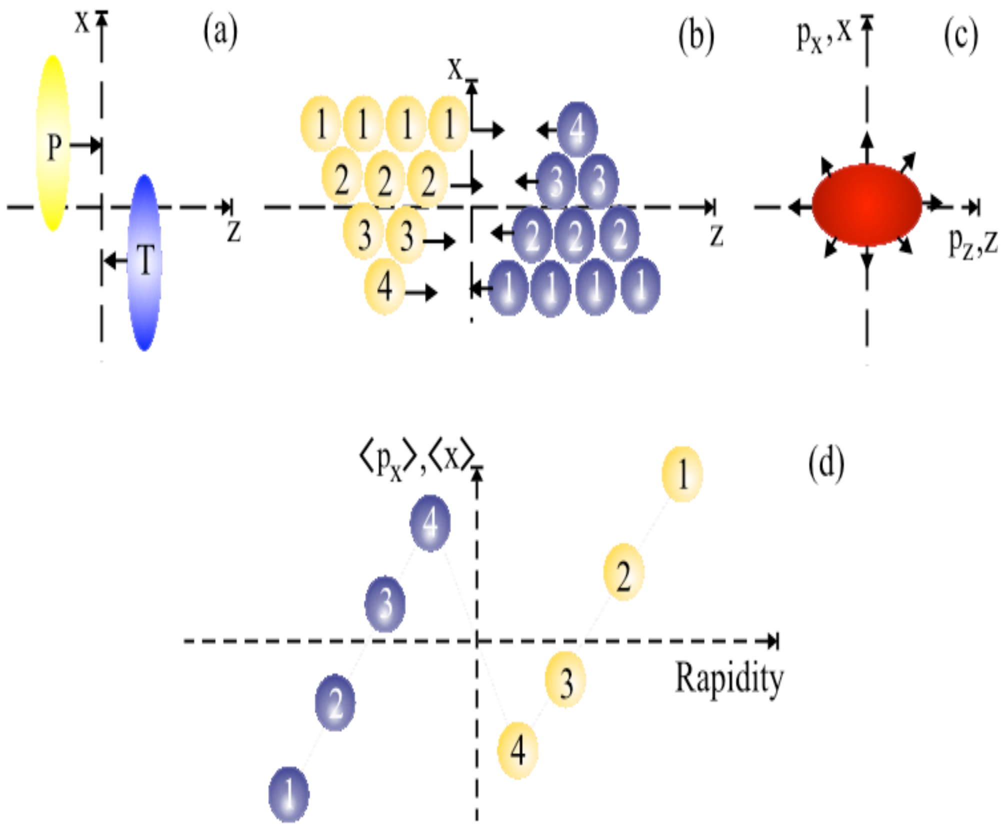


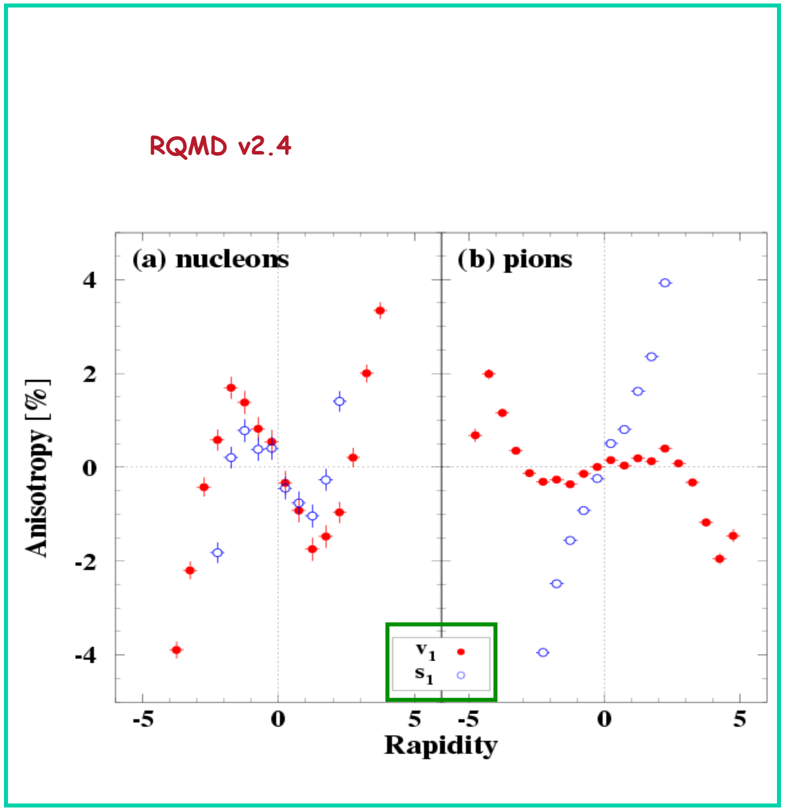


Brachmann, Soff, Dumitru, Stocker, Maruhn, Greiner Bravina, Rischke , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) M.Bleicher and H.Stocker, PLB 526,309(2002)

Anti-flow/3rd flow component : Flat v_1 at midrapidity due to 1st order phase transition
Caution : Seeing anti-flow does not necessarily mean that there is a phase transition. (refer to UrQMD).

v_1 from baryon stopping

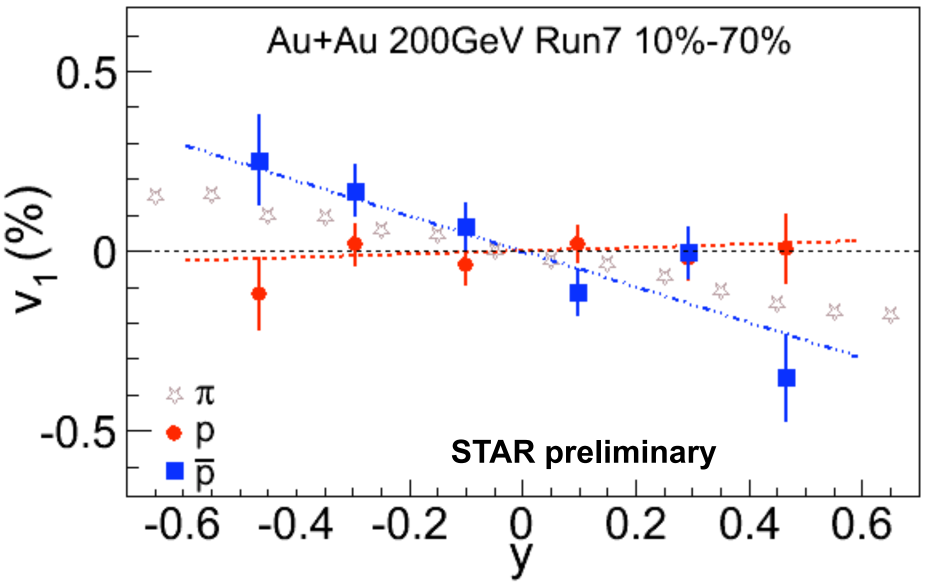


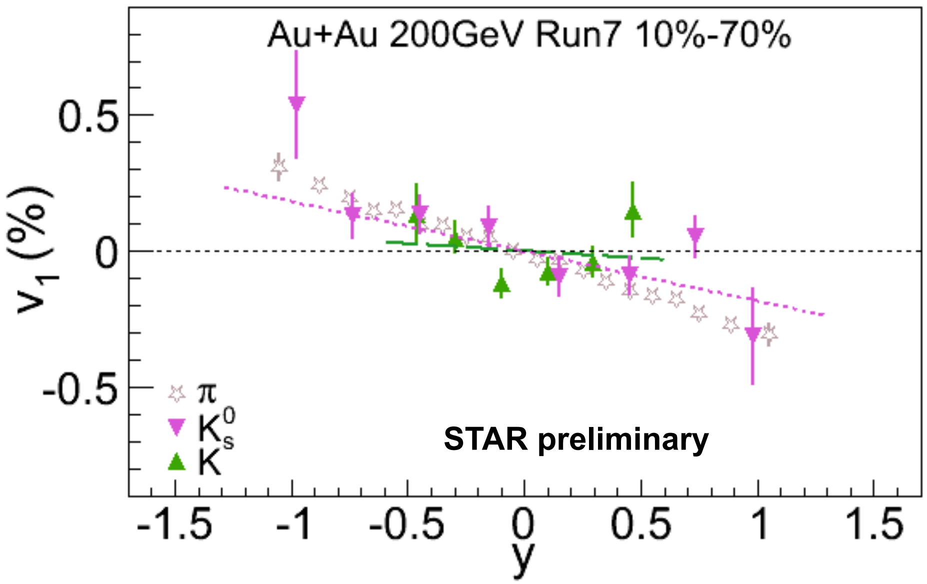


R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

Baryon stopping + positive space-momentum correlation → v_1 wiggle.
No QGP necessary

PID v_1





Proton 0.4<pT<1.0 (GeV/c)
Antiproton 0.4<pT<1.0 (GeV/c)

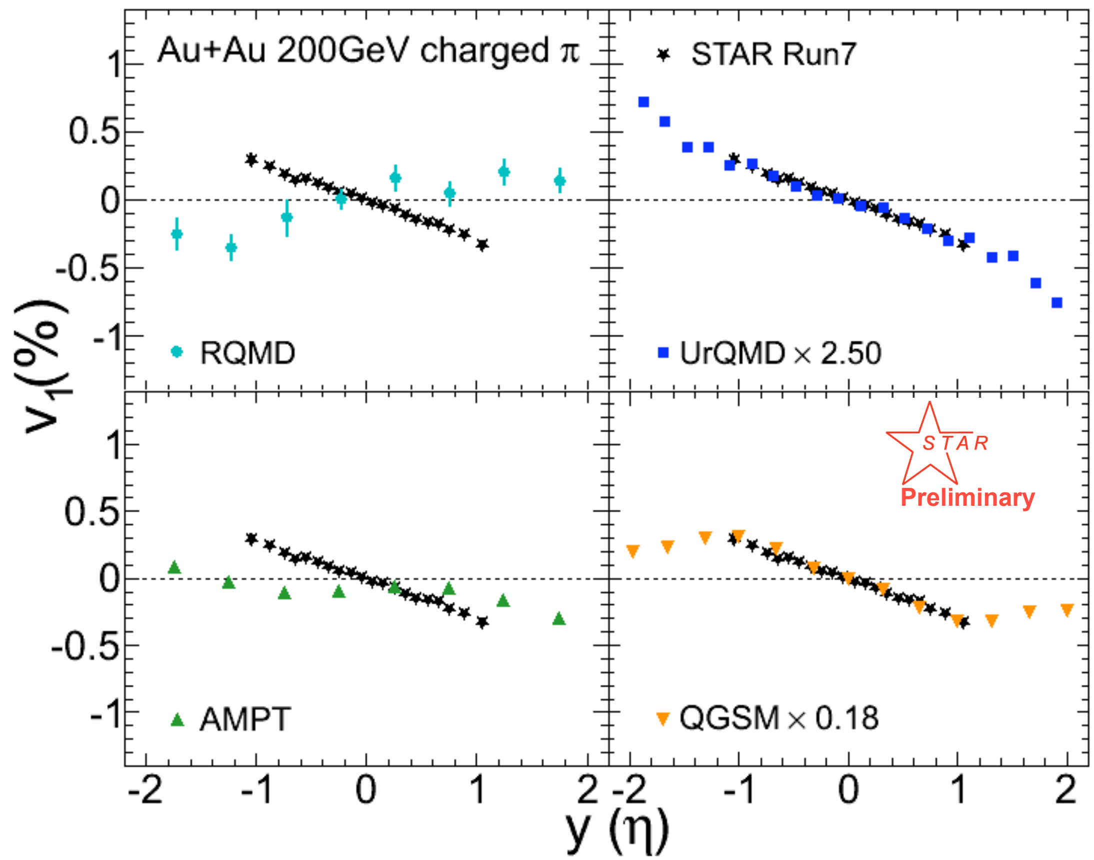
Pion 0.15<pT<0.75 (GeV/c)
Kaon 0.2<pT<0.6 (GeV/c)

First measurement of v_1 of anti-protons

Anti-proton slope has the same sign of pions – consistent with anti-flow

Kaon suffers less shadowing effect due to smaller k/p cross section, yet we found negative v_1 slope for both charged kaon and Kshort – consistent with anti-flow

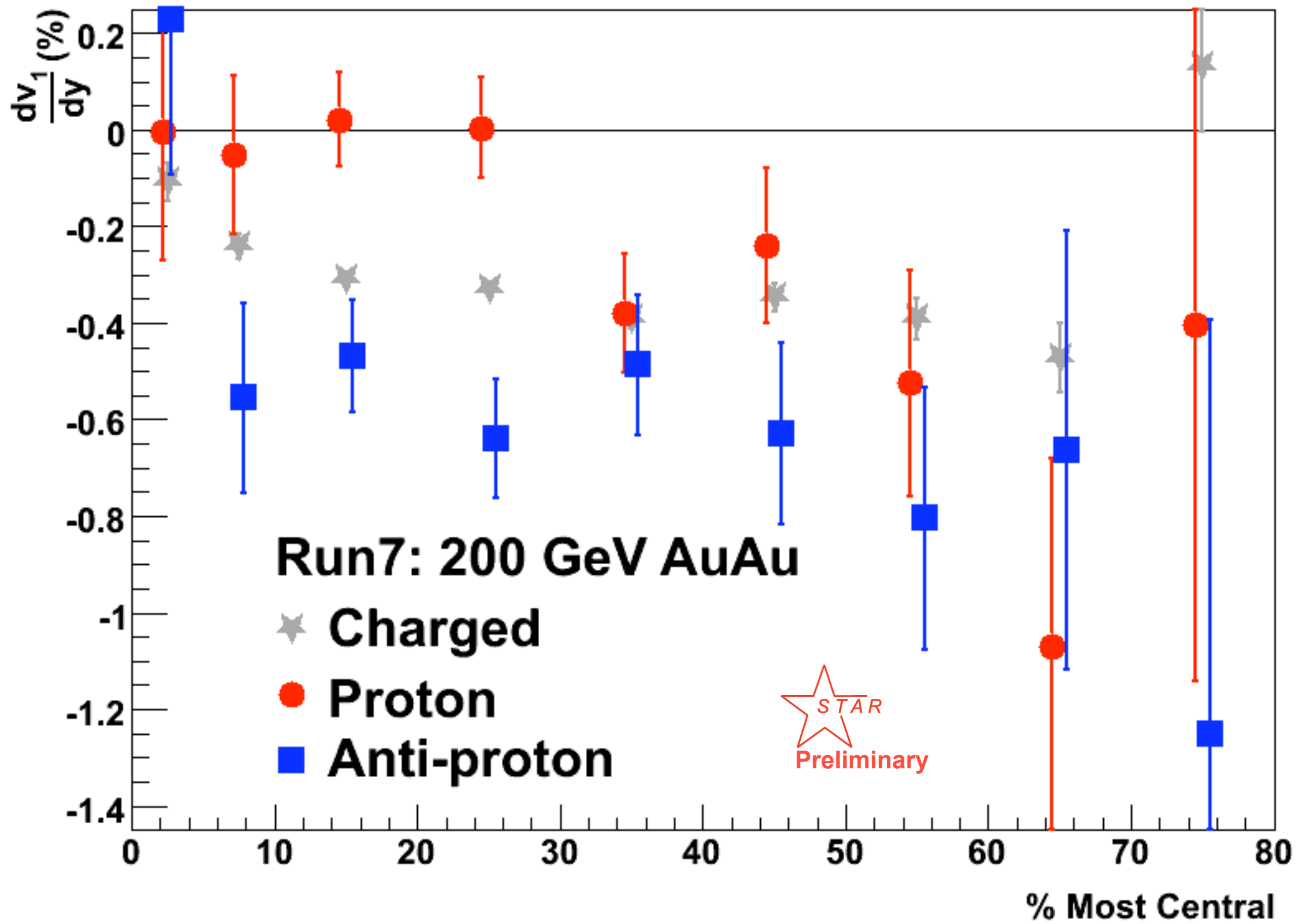
PID v_1



Phys. Rev. Lett. 84 (2000) 2803;
Phys. Lett. B 526 (2002) 309–314;
Phys. Rev. C 71, 054905 (2005).

So far no models can describe the data

Centrality dependence of v_1 slope



Large difference seen between v_1 of protons and anti-protons in mid-central collisions.
Does not match expectations.

Summary

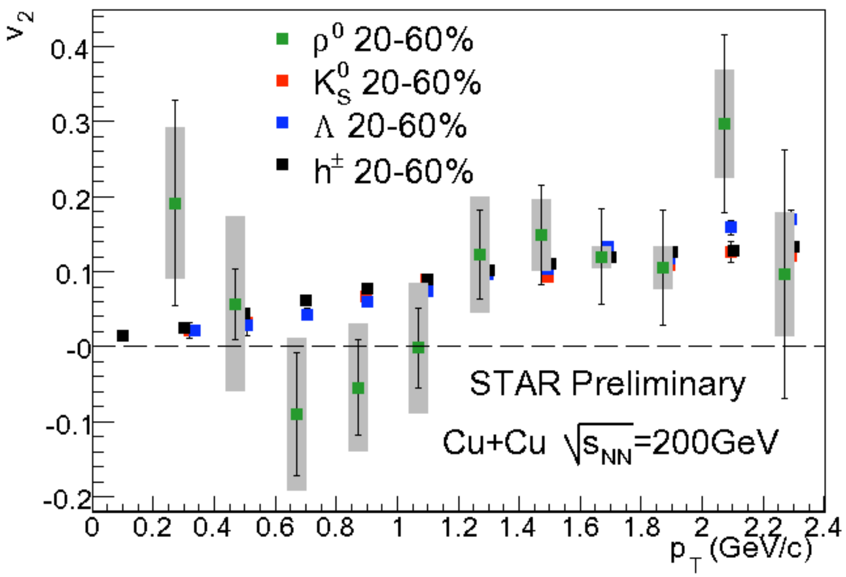
- **NCQ scaling is more complicated than it appears to be.**
  - **Pions deviate from NCQ scaling by 20% (while models can tolerate only 5%), kaons by 10%.**
  - **m_T (low p_t) and NCQ (intermediate p_t) are two separate scalings, they should not be confused/mixed.**

- **Knudsen Fit gives the upper limit of η/s**

- **The heavier the particle, the more curvature is seen in the plot of v_2/ε scaled by its saturation value, as a function of 1/S dN/dy. Such feature is not seen in Hydro models (ideal or viscous/hybrid), but is seen in AMPT.**

- **First measurement of antiproton v_1 is presented. v_1 at 200 GeV is consistent with anti-flow. Sizable difference is seen between v_1 of protons and anti-protons in mid-central collisions. So far no model can describe data.**

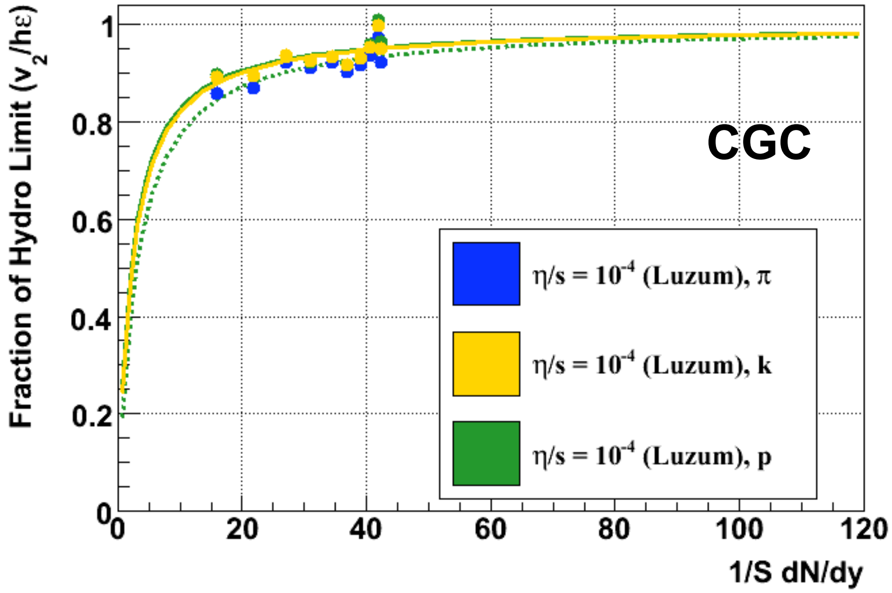
Future directions

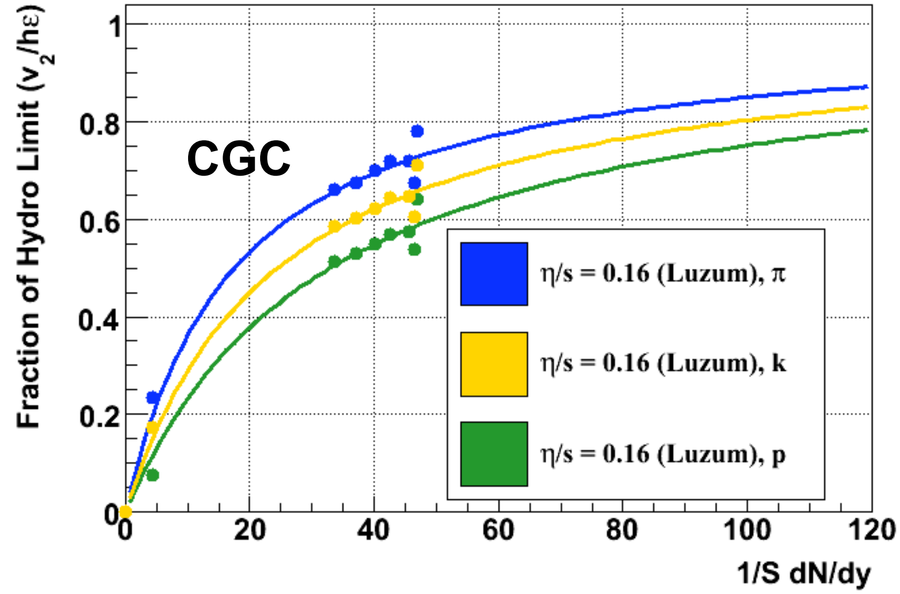


- **Heavy versus light : Does J/ψ flow? Does J/ψ v_2 fit into the mass hierarchy of v_2/ε vs. 1/S dN/dy curvature ?**
- **Soft versus Hard : Do ID'd particles follow their own groups after the expected breaking of NCQ scaling at large p_t ?**
- **Early versus late : What is the flow pattern of ρ^0 v_2 ?**
- **High versus low energy : How does the mass hierarchy of curvature changes with energy ?**
- **Precision measurement of PID v_1 : Is there any signature of 1st order phase transition ?**

Backup Slides

Can hydro explain the mass hierarchy of curvature ?

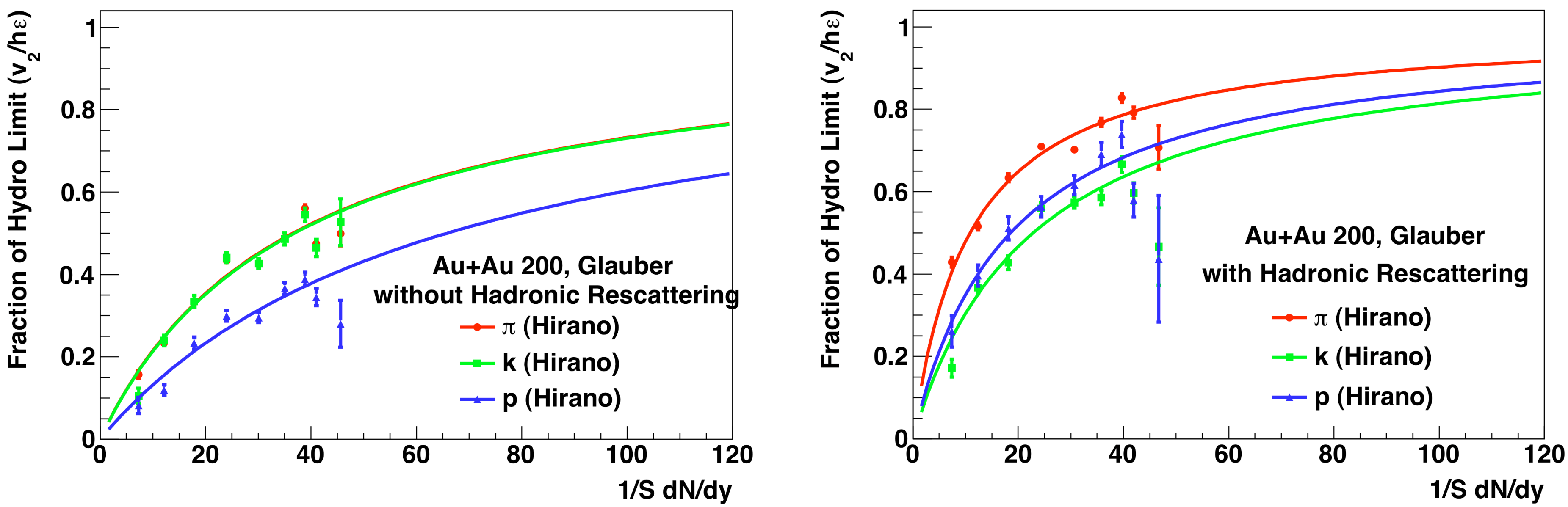




Ideal Hydro does not have the mass hierarchy of curvature.

Viscous Hydro gives the opposite order of mass hierarchy of curvature.

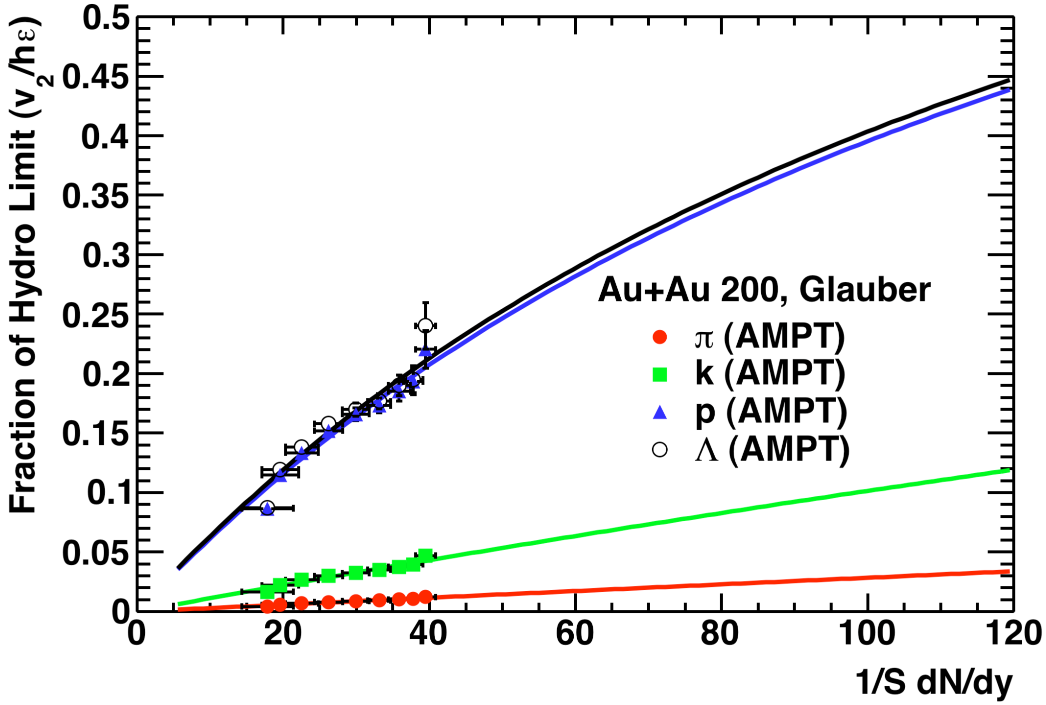
Can the hadronic rescattering explain the mass hierarchy of curvature ?



Plot courtesy : N. Li

Hadronic rescattering gives the opposite order of mass hierarchy of curvature.

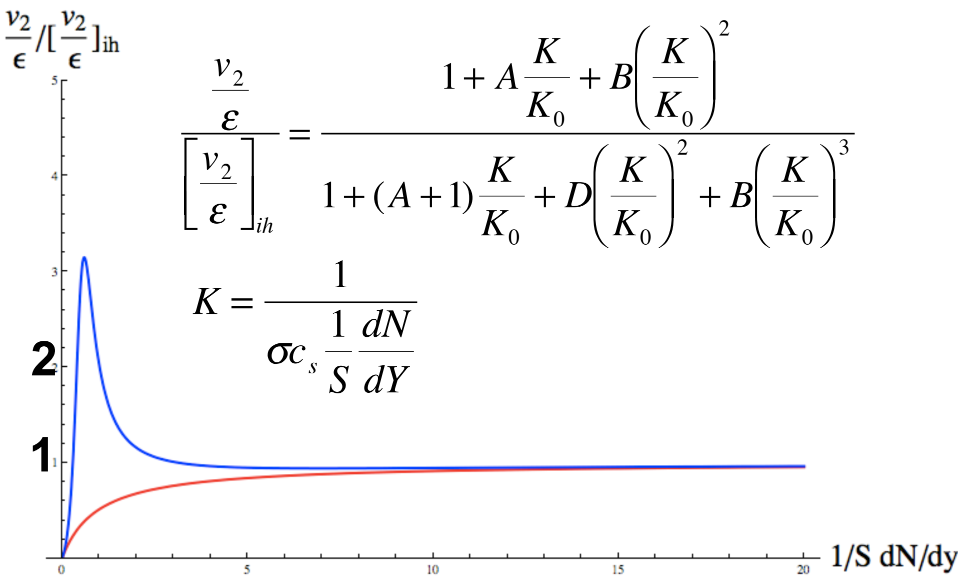
What does AMPT say ?



Plot courtesy : N. Li

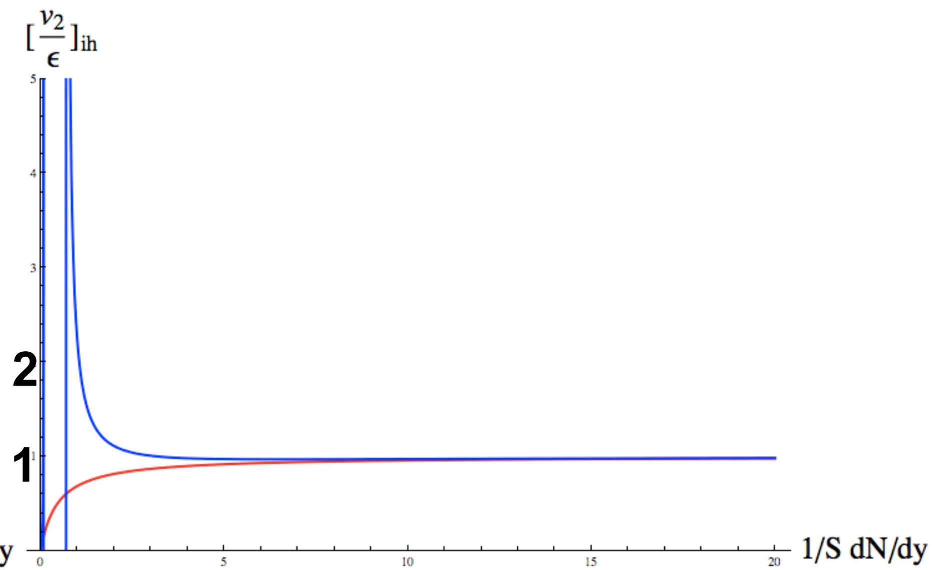
So far for models checked, only AMPT has the right order of mass hierarchy of curvature.

Comments on Pade Formula



$$\frac{\frac{v_2}{\varepsilon}}{\left[\frac{v_2}{\varepsilon}\right]_{ih}} = \frac{1 + A\frac{K}{K_0} + B\left(\frac{K}{K_0}\right)^2}{1 + (A+1)\frac{K}{K_0} + D\left(\frac{K}{K_0}\right)^2 + B\left(\frac{K}{K_0}\right)^3}$$

$$K = \frac{1}{\sigma c_s \frac{1}{S}\frac{dN}{dY}}$$



Higher order terms may cause wiggles.

When the wiggle effect is large, it may violate the boundary.

When the wiggle effect is small, it becomes the oscillation on top of the curvature defined by low order terms.

- •The oscillation can be picked up as part of the curvature.
- •The oscillation may have long wave-length to make the formula to appear as "well behaved".